Wavelength switching and light modulation in laser diodes with nonidentical multiple quantum wells

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ABSTRACT

The wavelength of the designed two-section laser diode can be modulated by direct current modulation. The modulation speed of intensity of each wavelength is 1.5 times faster than the speed of a direct modulated single section laser. The modulation depth of output intensity can be 20dB.

Keywords: laser diode, two section, two wavelength, wavelength switching, intensity modulation

1. INTRODUCTION

A communication system is composed of receivers, signal path, and transmitters. Using light as the signal carrier is advantagous over using electrical signals or RF signals because the light signals suffer less distortion and loss [1][2]. Thus, the bit rate can be higher and communication distance can be longer. In addition, different channels can use the same signal path because signals carried by different wavelengths do not interact with each other [3]. To fully take the advantage of light, high-speed and broad wavelength bandwidth receivers and transmitters are required. Detectors with 40GHz bandwidth are developed early and are commercially available. Detectors with more than 100GHz bandwidth are under development and will be commercially available, soon. However, the speed and wavelength bandwidth of light sources available is far below the requirement. The only 40GHz transmitters commercially available now are assembled from CW light sources and light modulators [4][5][6]. The wavelength bandwidth of these systems are mostly below 30nm because of the difficulty to integrate wavelength tuning elements on laser diodes [7]. In addition, these transmitters have higher production cost, require more space and more power. Thus, the research efforts to increase the speed of direct modulated laser diodes are never stopped. Currently, the speed of commercially available lasers is about 10Gb/s. Laser diodes with 22GHz modulation bandwidth is developed on quantum dot structures because it has the unique delta function like density of states and high differential gain [8]. The fastest laser diode developed to date, which has 43GHz bandwidth, is the tunneling injection quantum well laser because the carriers can flow in and out quickly by tunneling [9]. For applications that requires more than 43GHz bandwidth, there is no suitable direct modulated light sources. Here we propose a new type of laser design in which the laser wavelength can be switched by changing the injection current. In addition, the intensity modulation of the laser oscillations can be faster than normal quantum well lasers for its unique wavelength switching mechanism.

2. DEVICE DESIGN AND FABRICATION

The device proposed is a Fabry-Perot Laser diode with two-section waveguide fabricated on an InP substrate. The active layer consists of two quantum wells designed for 1.5μm wavelength emission and three quantum wells designed for 1.3μm wavelength emission. The two types of quantum wells are inserted between each other as shown in the following figure.

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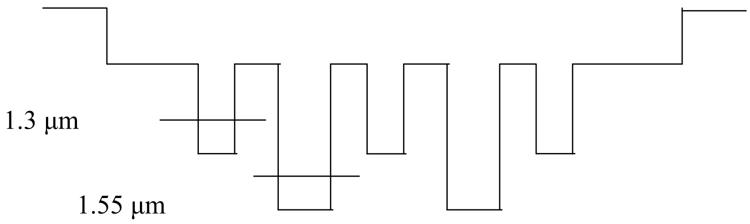


Figure 1: The active layer structure.

The devices use double channel ridge waveguides. The waveguide is 3µm in width. The channel is etched by RIE. The process gas is CH_4 and H_2. The etched depth is 100~200nm above the undoped optical confinement layer. As shown in Figure 2, the gap between two waveguide sections is also etched during waveguide etching process. Thus, the p-cladding of the two sections are electrically isolated. The optical confinement layer is not etched. Thus, the light passing from one section to the other will not be reflected by air-semiconductor interface.

After the waveguide is created by dry-etching, 3kÅ PECVD oxide is applied as insulation layer. The oxide grown on top of the waveguide is removed by self align technique. The p-side contact is Ti/Pt/Au deposited by an e-beam evaporator. The thickness is 0.5kÅ/0.75kÅ/4.5kÅ. For devices used in frequency response measurement, the Ti/Pt/Au bonding pad is reduced to 70µm x 70µm in order to reduce the parasitic capacitance of the p-metal/oxide/semiconductor three-layer structure. Finally, the wafer is lapped to 100µm thick and cleaved into devices. As shown in Figure 3, the cleaved device is 1mm in length. It has two sections of 500µm waveguides.

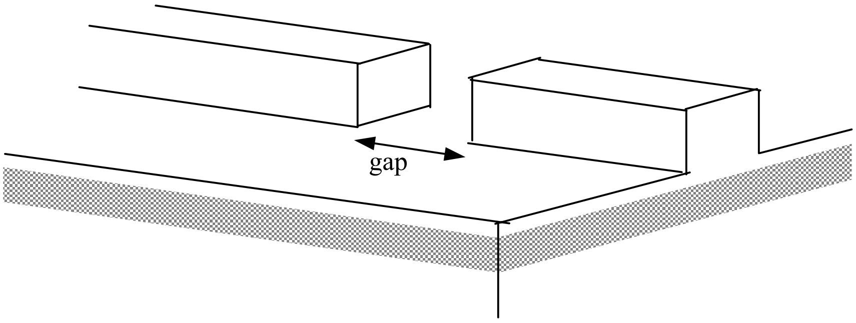


Figure 2 : The etched gap between two waveguide sections. The red area is the active region.

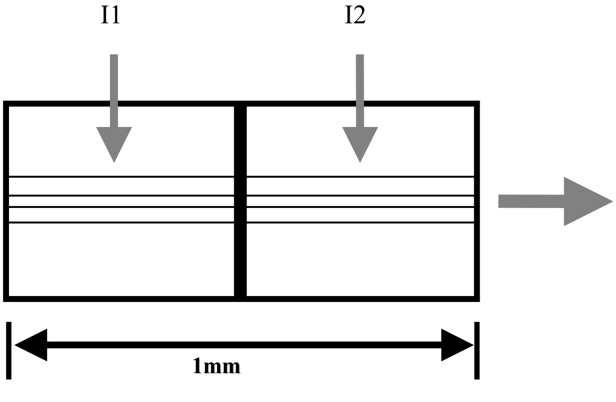


Figure 3 : The fabricated two section laser diode.

3. THE MODEL OF WAVELENGTH SWITCHING

Because the gain profile of the designed quantum well varies with the injected current density [10], the combined gain profile will change as the relative injected current density changes. As shown in Figure 4, the dot line is the gain contributed by I2 and dash-dot line the gain contributed by I1, assuming I2 is larger than I1. The gain contributed by I2 is peaked at λ2. When I2 is increased, the gain contributed by I2 to both λ1 and λ2 will increase. However, the increase of gain at λ2 will be more than the increase of gain at λ1 because the gain contributed by I2 to λ1 is saturated due to the band-filling effect. Thus, the laser oscillation at λ2 will increase. In addition, the increased oscillation at λ2 will suppress the carrier population contributed by I1, and the gain contributed by I1 to λ1 will decrease, leading to decrease of laser oscillation intensity at λ1. When I1 is increased, the gain contributed by I1 to both λ1 and λ2 will increase, too. However, because of the lower injection level of I1, band-filling effect does not dominate. The increased carriers will populate lower states and contribute more gain to λ1 than to λ2. As a result, the laser oscillation at λ1 will increase. Also, the increased laser oscillation at λ1 will suppress the population contributed by I2 and leads to the decrease of laser oscillations at λ2.

During the switching process, the changes of carrier populations in the two sections have different reasons. For instance, when I1 is increased, the carriers in section 1 are increased due to increase of I1. This will lead to the increase of laser intensity at λ1. Then, laser oscillations at λ1 will compete with laser oscillations at λ2 for carriers contributed by I2, resulting in carriers, which originally populate at higher energy levels, fall to lower energy levels. Hence the increased oscillation intensity at λ1 has two sources of contribution. One is the increased current, I1. The other is the carrier, which are initially at higher energy states. These carries fall to lower states because of gain competition and so contribute optical gain to λ1. The transition time between any two states in the active layer is much less than the time required for carrier to travel from the electrical contact layer to the active layer. Thus, the carrier population should be able to reach equilibrium faster than a single section laser diode, which does not have two oscillation wavelengths.

$$G_{th} = \alpha_i + \frac{1}{L}\ln\left(\frac{1}{R_1 R_2}\right)$$

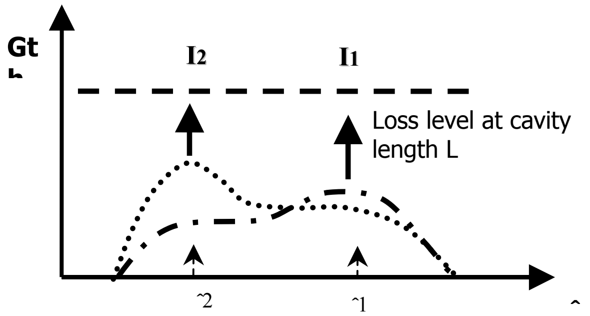


Figure 4: By controlling I1 and i2, the shape of total gain spectrum can be changed, leading to change of oscillation wavelength.

STEADY STATE RESPONCE

For steady state response measurement, the device used has 10µm gap. It is mounted on a copper heat sink and a gold wire is bonded on each contact by indium solder as shown in Figure 5. To reduce the effect of heating, two HP8114A pulse source is used as current source for this device. The output pulses have 1kHz repetition rate and 1µs width. The output from one facet is collimated to a multimode fiber and sent to an optical spectrum analyzer. From another facet, the two groups of laser oscillations are separated by a grating and collected by two detectors as shown in Figure 6. In Figure 6, the symbols "I1" and "I2", which are used to denote the currents flowing through each section, are also defined in the same way. When I1 is 45.6mA and I2 is 12m, this device can oscillate at 1530nm, as shown in Figure 7(a). If we increase I2, another group of oscillation modes appear at 1537nm. The peak intensities of the two groups are equal when I2 is 14.4mA. If I2 is increased further, the 1537nm group of oscillation will dominate. Similar situation occurs when I2 is fixed and I1 is increased (Fig. 8). However, increasing I1 will increase the group of 1530nm oscillations and suppress the group of 1537nm oscillations.

By collecting the two groups of oscillation modes in two detectors, the total power of each group is recorded. When I1 is fixed at 45.6mA and I2 is increased from 12mA, both intensities of 1530nm and 1537nm oscillations will increase initially as shown in Figure 9(a). When I2 reached 14mA, the oscillations at 1537nm begin to compete with oscillations at 1530nm. The intensity of 1530nm oscillation begins to drop and intensity of 1537nm oscillations increases sharply. Within 5mA variation of I2, the intensity of oscillations at 1537nm increased by 22dB, and the intensity of 1300nm oscillations drop by 17dB from the peak. Increasing I1 can increase the intensity 1530nm oscillations by 21dB and decrease the intensity of 1537nm oscillations by 19dB as shown in Figure 9(b).

In the case of this device, I1 is larger than I2. Increasing I1 will increase the intensity of shorter wavelength oscillations and suppress the intensity of longer wavelength oscillations. Similar behaviors can be observed on other devices when switching is observed with large I1, I2 difference. Such as the data shown in Figure 10, I2 varies from 22.4mA to 25.2mA, while I1 is kept at 39.2mA. Increasing I2 will increase the oscillation at 1527nm, which is of longer wavelength. When the difference between I1 and I2 is small, this role of I1 and I2 may change. In Figure 11, I1 is 48.8mA while I2 is increased from 42.2mA to 48mA. Increasing I2 leads to the increase of 1499nm oscillation, which is the shorter wavelength part.

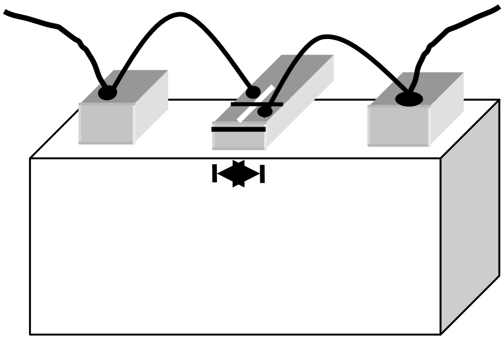


Figure 5 : The bonded device.

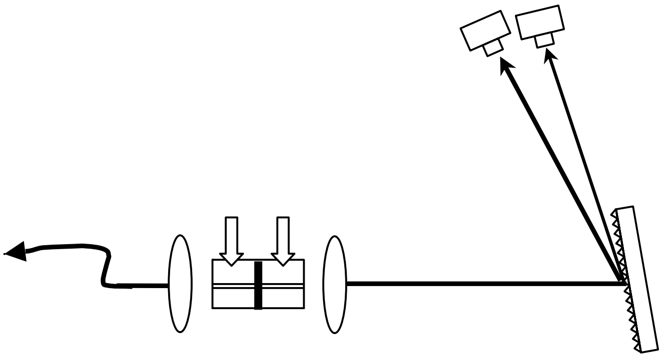


Figure 6 : The setup for power and spectrum measurement.

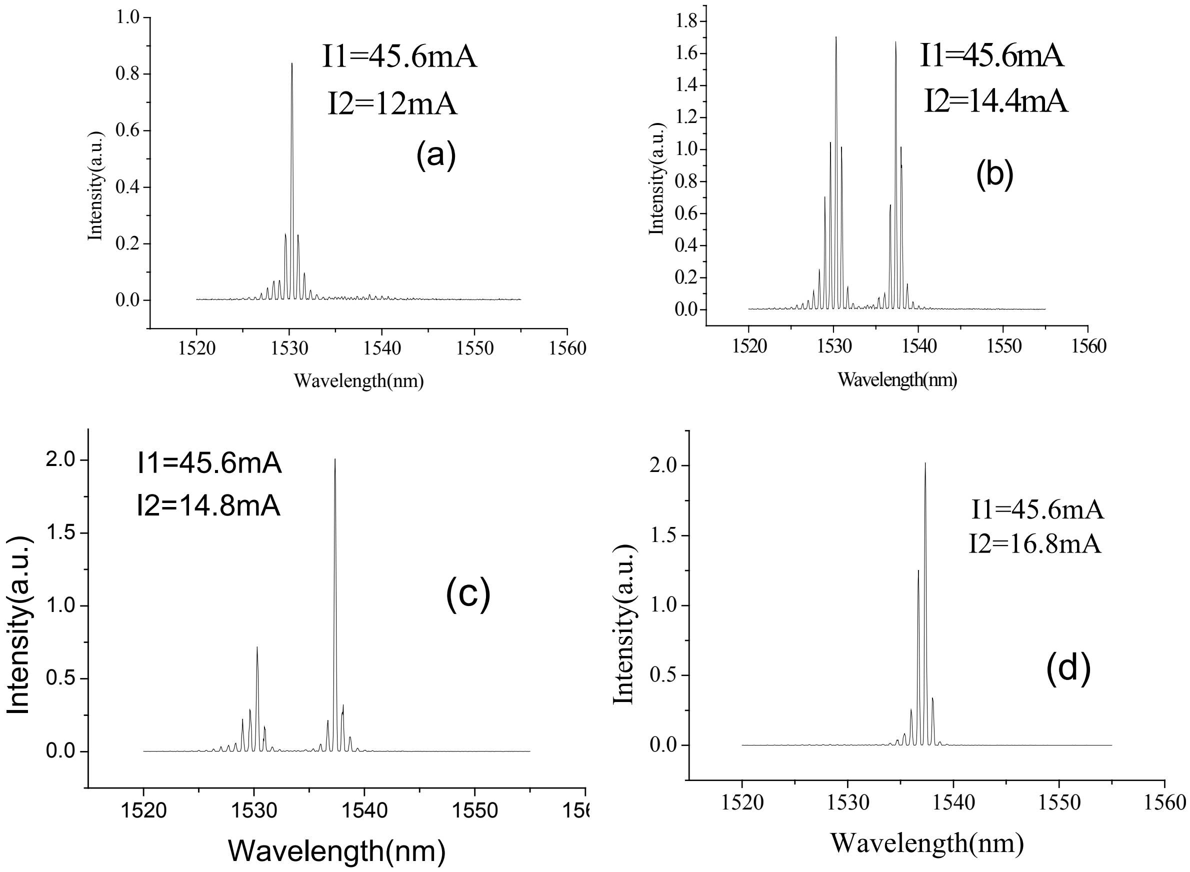


Figure 7 : The output spectrum when I1 is fixed and I2 is increased from 12mA to 16.8mA.

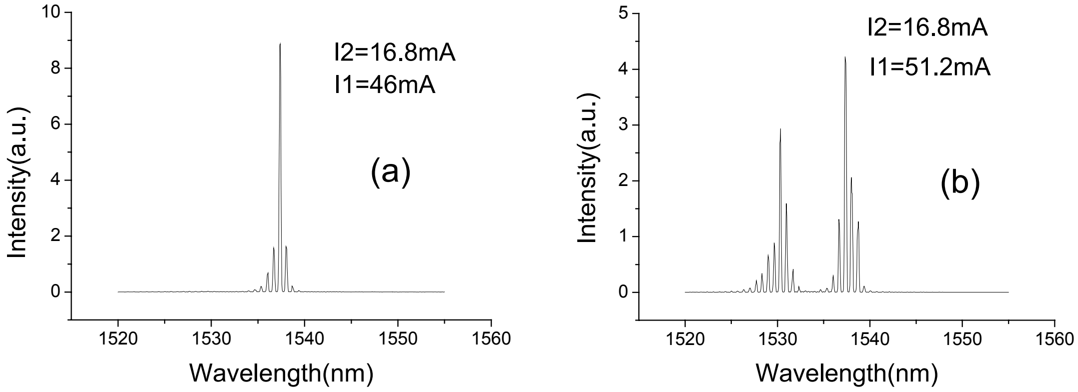


Figure 8 : The output spectrum when I1 is increased from 46mA to 58.8mA, while I2 is fixed, (a) and (b).

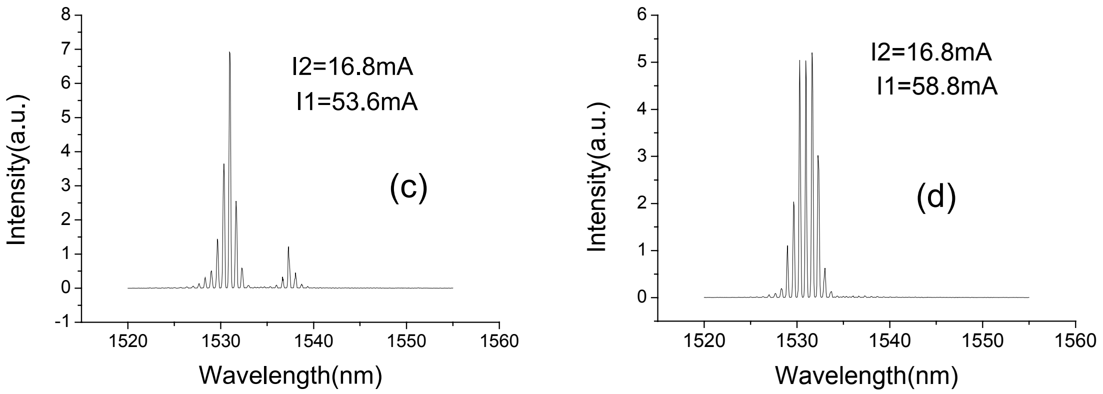
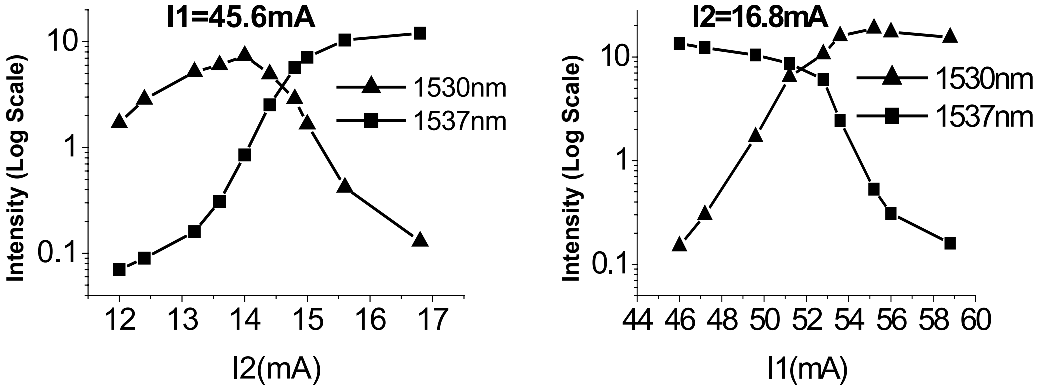


Figure 8 : The output spectrum when I1 is increased from 46mA to 58.8mA, while I2 is fixed, (c) and (d)..



(a)I1 fixed, I2 varied

(b)I2 fixed, I1 varied

Figure 9: The output intensity of the two groups of oscillation modes as current is varied

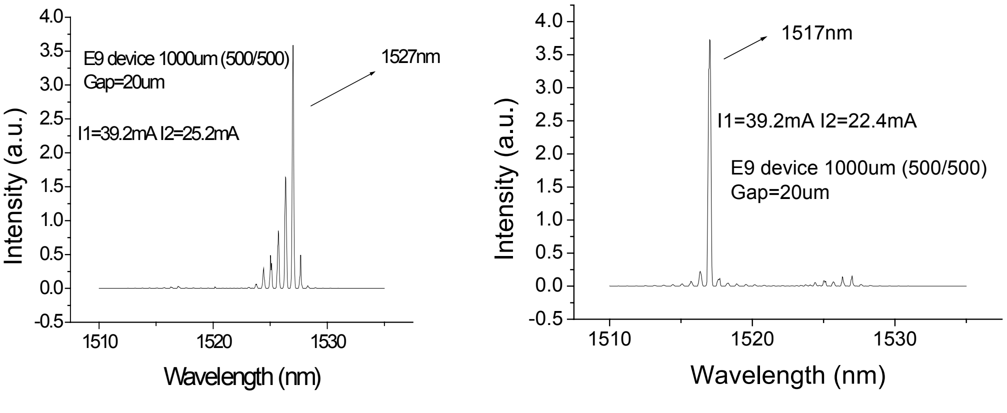


Figure 10: The variation output spectrum with current of another device, which also has large I1 I2 difference.

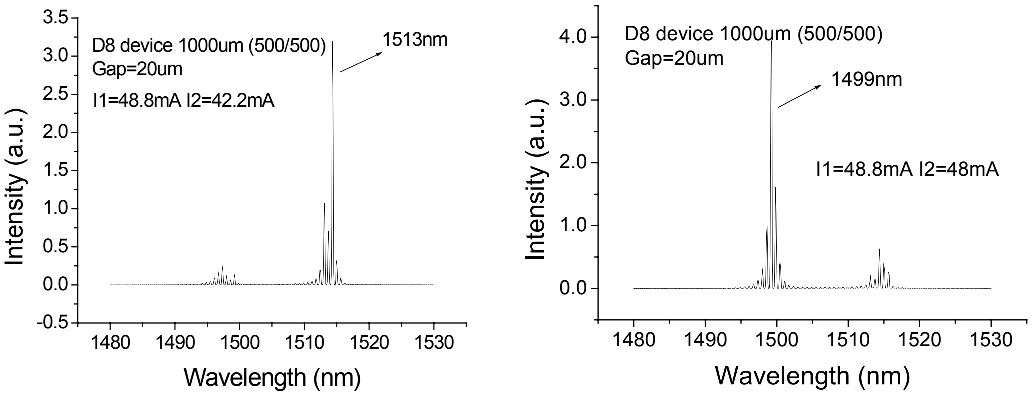


Figure 11: The variation output spectrum with current of a device, which has small I1 I2 difference.

RF RESPONCE

If these lasers are going to be used as a light source in communication network, it will be necessary to know how fast the wavelength switching can occur. Thus, we apply RF signals to these devices and measure the intensity variation of both oscillations as shown in Figure 12. The RF source is HP83732B synthesizer. An amplifier is added to increase the signals injected into the device. The two groups of laser oscillations are separated using a grating, focused to single mode fibers and fed to high-speed InGaAs detectors. The measured device is 1mm in length. The two waveguide sections are 500μm each. The gap between waveguides is 20μm. To prevent RF source being damaged by noise from HP8114A pulse source, the section to which RF is applied using a DC current source. The other section still uses HP8114A as current source. This device is biased at the point in which both groups of oscillations have equal output power, 0.8mW. The two oscillation groups are at 1514nm and 1523nm respectively. Figure 13 is the measured current-light transfer function at different frequency. As shown in Figure 13, the frequency response of the two-section device has a resonance at 1.5GHz for both wavelengths. The resonance frequency of a single section device fabricated on the same wafer and biased at 1.8mW output is at 1GHz. After the resonance frequency, they have the same 50dB/decade drop. Thus, the response of a two-section device with two laser wavelength outputs is 1.5 times faster than a single section device with only one wavelength laser output.

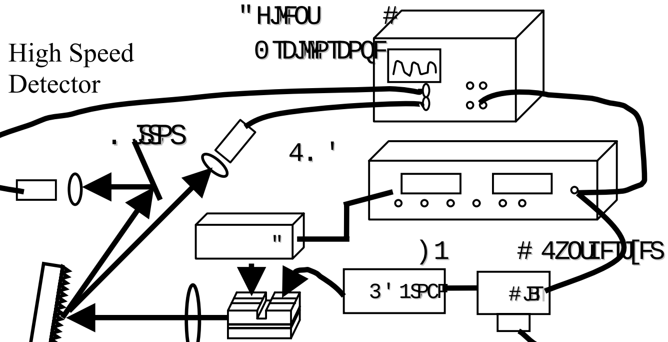


Figure 12: The setup for frequency response measurement.

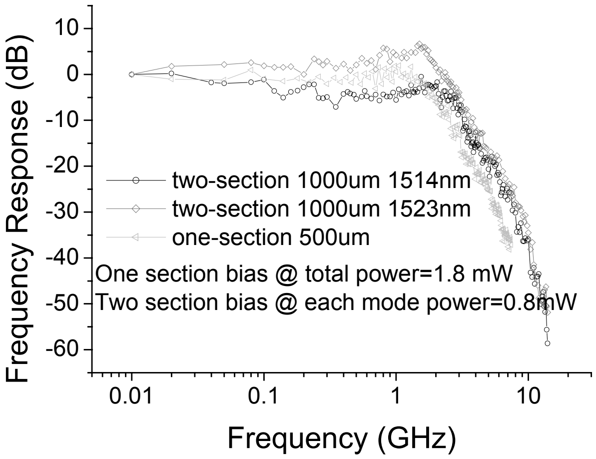


Figure 13: The current-light transfer function of two-section device and single section device.

CONCLUSION

This designed two-section laser diode is capable of providing two laser wavelengths. Laser wavelength can be modulated by direct current modulation. The output intensity at each wavelength can be varied by 20dB. The speed of intensity modulation of each wavelength is 1.5 times faster than the speed of a direct modulated single section laser because a part of the carriers only need to take transitions between different energy states within the active layer to retain equilibrium.

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